

# Dark impact and galactic star formation: Origin of the Gould belt

Kenji Bekki<sup>1\*</sup>

<sup>1</sup>*School of Physics, University of New South Wales, Sydney 2052, NSW, Australia*

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## ABSTRACT

The Milky Way has a giant stellar structure in the solar neighborhood, which has a size of  $\sim 1$  kpc, a mass of  $\sim 10^6 M_\odot$ , and a ring-like distribution of young stars. Fundamental physical properties of this local enigmatic structure, known as the Gould belt (GB), have not been reproduced by previously proposed models. We first show that the local enigmatic structure can be formed about 30 Myr ago as a result of a high-speed, oblique collision between a gas cloud with a mass of  $\sim 10^6 M_\odot$  and a dark matter clump with a mass of  $\sim 10^7 M_\odot$  based on numerical simulations of the collision. We find that strong dynamical impact of the clump transforms the flattened cloud into a ring-like stellar structure after induced star formation within the cloud. Our simulations furthermore demonstrate that the stellar structure is moderately elongated and significantly inclined with respect to the disk of the Milky Way owing to the strong tidal torque by the colliding clump. We thus suggest that the GB is one of stellar substructures formed from collisions between gas clouds and dark matter clumps predicted in the hierarchical clustering scenario of galaxy formation. We also suggest that collisions of dark matter clumps with their host galaxies can significantly change star formation histories for some of their gas clouds thus influence galactic global star formation histories to some extent. Our simulations predict that unique giant stellar substructures recently discovered in other galaxies can result from dynamical impact of their dark matter clumps on their gas clouds.

**Key words:** The Galaxy – galaxies:structure – galaxies:kinematics and dynamics – galaxies:halos – galaxies:star formation

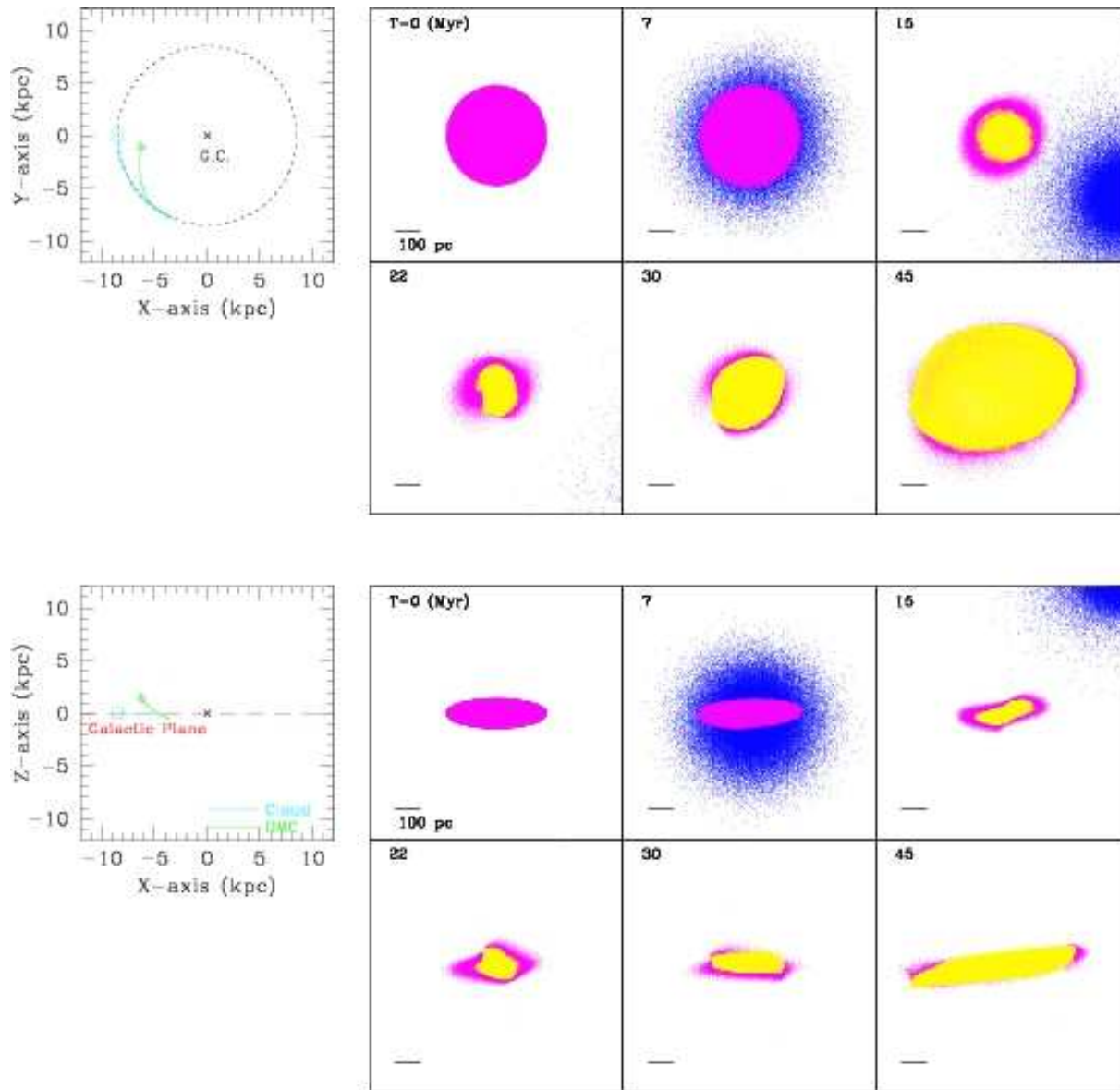
## 1 INTRODUCTION

The GB is a flattened stellar structure with an inclination of  $16^\circ - 22^\circ$  to the Galactic plane and contains about 60% of young stars with ages of 30 – 60 Myr within 600 pc from the Sun (e.g., Olano 1982; Poppel 1997; Guillout et al. 1998; Torra et al. 2000). The projected distribution of young stars in the GB is suggested to be quite inhomogeneous and significantly elongated with an ellipticity of  $\sim 0.3$  (e.g., Poppel 1997). The observed stellar kinematic of the GB suggests that the GB has internal rotation with a possible angular velocity of  $7 - 24 \text{ km s}^{-1} \text{ kpc}^{-1}$  and is currently expanding (Lindblad 2000). The GB is considered to be young with its age less than 30 – 60 Myr (e.g., Poppel 1997). Previous theoretical studies suggested that the formation of the GB is closely associated with efficient star formation in an expanding gaseous ring formed as a result of stellar feedback effects of massive OB stars and supernovae on interstellar medium

in the solar neighborhood (e.g., Poppel 1997). Other studies (e.g., Comeón & Torra 1994) proposed an oblique impact of a high-velocity cloud on the gas in the Galactic disk for the GB formation.

The purpose of this paper is thus to propose a new scenario which explains self-consistently the observed fundamental properties of the GB. In the new scenario presented in this paper, the GB is one of stellar substructures (e.g., rings and arcs) formed from high-speed, off-center collisions between giant molecular clouds, which are believed to be the birth places for stars (Lada & Lada 2003), and dark matter clumps (DMCs) orbiting the Galaxy. This dynamical impact of DMCs is referred to as the dark impact for convenience in Bekki & Chiba (2006) and used as such in the present paper. Since recent high-resolution cosmological simulations of the Galactic halo formation based on the cold dark matter model (CDM) have shown that hundreds of high-density DMCs may exist in the solar-neighborhood (Diemand et al. 2008), we consider that such collisions between gas clouds and DMCs are almost inevitable. We here do not intend to

\* E-mail: bekki@phys.unsw.edu.au



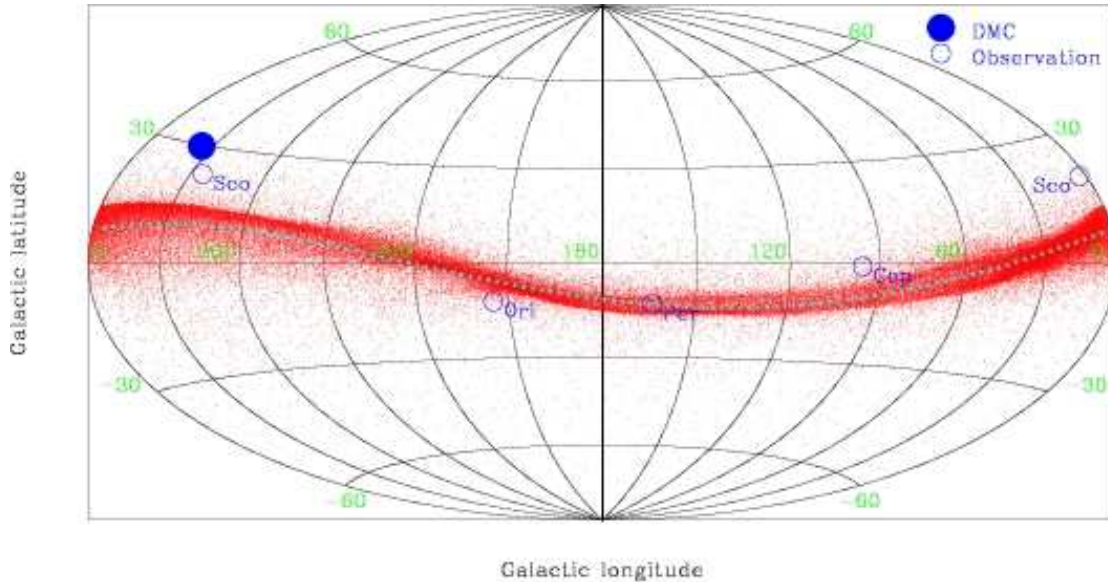
**Figure 1.** Morphological evolution of a gas cloud colliding with a dark matter clump (DMC) projected onto the  $X$ - $Y$  plane (upper) and the  $X$ - $Z$  one (lower). The time  $T$  (in Myr) shown in the upper left corner of each panel represents the time that has elapsed since the simulation started. The two separate panels show the orbits of the cloud (cyan) and the DMC (green) projected onto the  $X$ - $Y$  and the  $X$ - $Z$  planes. The final locations of the cloud and the DMC indicated by an open square and an open triangle, respectively, and the solar radius ( $R = 8.5$  kpc corresponding to the distance between the Sun and the Galactic center, G.C.) and the Galactic plane are shown in these two panels for comparison. The cloud and the DMC are represented initially by 150000 gaseous particles and 100000 stellar ones, respectively, and shown by magenta and blue, respectively. The yellow particles are new stars formed from gas in the cloud. A bar shown in the lower left corner of each frame measures 100 pc. The time evolution of the cloud-DMC distance is described in Fig. 3, which clearly shows that the cloud-DMC collision is an off-center one.

discuss the well known over-abundance problem of satellite galaxies (hosted by dark matter subhalos) in the CDM, just because this is beyond the scope of this paper.

## 2 THE MODEL

We here show the results of GRAPE-SPH simulations (Bekki & Chiba 2007) only for the best model explaining the observed properties of the GB self-consistently, and will describe those of other models with different model parameters

in our future study (e.g., Bekki 2009 in preparation, B09). The progenitor cloud of the GB is modeled as an oblate sphere with a radius of 200 pc, an ellipticity of 0.3, a mass of  $10^6 M_\odot$ , temperature of 100K, and rigid rotation with an angular velocity of  $4.8 \times 10^{-2} \text{ km s}^{-1} \text{ pc}^{-1}$ . These parameters values are consistent with the observed properties of GMCs (e.g., Solomon et al. 1979; Kerton et al. 2003; Rosolowsky et al. 2003). GMCs with sizes of  $\sim 100$ pc exist in the Galaxy (e.g., Fig. 6 in Solomon et al. 1979), and those with sizes of 100 – 200pc exist in other galaxies (e.g., NGC 4449 and NGC4605; see Fig. 1 in Bolatto et al. 2008). Therefore, given



**Figure 2.** Final distribution of stellar particles in the cloud at  $T = 45$  Myr in the Galactic coordinate system, where abscissa and ordinate denote Galactic longitude ( $l$ ) and latitude ( $b$ ), respectively. All stellar and gaseous particles are shown by red and the final location of the DMC is shown by a filled blue circle for comparison. The five blue open circles represent the observed OB associations on the Gould Belt (de Zeeuw et al. 1999): two OB2 in Scorpion constellation (Sco), OB 1 in Orion (Ori), OB2 in Perseus (Per), and OB2 in Cepheus (Cep). Only one of the listed locations in de Zeeuw et al. (1999) for each OB association is shown here for convenience (e.g.,  $(l, b) = (164^\circ, -13^\circ)$  for Per OB2). The dotted thick cyan line describes the best-fit Gould curve (Taylor et al. 1987) of  $b = b_0 \sin(\frac{\pi}{180}[l - l_0]) + b_c$  for the simulated stellar belt, where  $b_0$  ( $\approx 12^\circ$ ),  $l_0$  ( $\approx 232^\circ$ ), and  $b_c$  ( $\approx -2^\circ$ ) denote the inclination angle of the belt with respect to the Galactic plane, the ascending node longitude of the belt, and the vertical distance between the mass center of the belt and the Galactic plane, respectively. The simulated Gould curve is more similar to that derived from the observed molecular clouds (Taylor et al. 1987) than to those from young stars (Poppel 1997; Perrot & Grenier 2003).

the observed uncertainties in estimating the GMC sizes (Bolatto et al. 2008), the adopted cloud sizes are consistent with observations for very large GMCs. Star formation is assumed to happen in local regions of the cloud if the regions satisfy physical conditions for the Jeans instability that can cause collapse of interstellar gas and subsequent star formation (e.g., Bekki & Chiba 2007).

The self-gravitating cloud is dynamically influenced by the fixed gravitational potential of the Galaxy composed of bulge, disk, and dark matter halo. We adopt the same Galactic potential as that used in Helmi & de Zeeuw (2000) which investigated orbits of dwarf galaxies in the Galactic halo. The cloud is located initially at 8.5 kpc from the Galactic center (G.C.) and moves round the Galaxy with a circular speed of  $220 \text{ km s}^{-1}$ . The present location of the Sun is set to be  $(X, Y, Z) = (-8.5, 0, 0)$  kpc and the Galaxy rotates to the  $+Y$  direction in the present study. The initial location and velocity for the cloud are chosen such that the final (i.e., present) location can be almost the same as that of the Sun after its 45 Myr evolution (see Fig.1 for the initial three-dimensional position in the Galaxy).

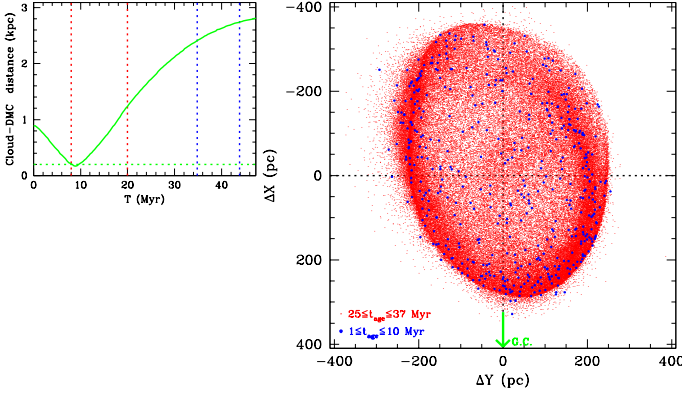
The DMC has a mass of  $3 \times 10^7 M_\odot$ , a mean density of  $2.0 M_\odot \text{ pc}^{-3}$  within 100 pc, and the NFW radial density profile (Navarro et al. 1996) within its tidal radius ( $= 317$  pc), which are all consistent with predictions from the latest cosmological simulations (Diemand et al. 2008; Springel et al. 2008a). The initial relative position  $(X_r, Y_r, Z_r)$  and velocity  $(U_r, V_r, W_r)$  of the DMC with respect to the cloud are set to be  $(-446, 233, -600)$  pc and  $(59, -29, 66)$   $\text{km s}^{-1}$ , respectively. For these relative positions and velocities,

the DMC collides with the cloud at  $T \approx 8$  Myr, where  $T$  represents the time that has elapsed since the simulation started.

We have confirmed that (i) the ring-like structure can be formed in models with a wider range of model parameters (e.g., impact parameter) and (ii) the dark impact of DMCs with masses of  $\sim 10^7 M_\odot$  can not influence structure and kinematics of the old stellar disk (B09). The origin of unique giant stellar substructures like the GB found in disks for a number of galaxies (Efremov & Elmegreen 1998; Comerón 2001; Larsen et al. 2002) and the “shingles” in the Galaxy (e.g., Schmidt-Kaler & Schlosser 1973) can be also explained in the context of the dark impact (B09). The simulated inclination angle of the GB is slightly smaller than the observed one, which may be one of disadvantages of the model: however, the inclination angle depends on (i) the time step at which it is estimated and (ii) the assumed location of the Sun owing to the precession of the GB.

### 3 RESULTS

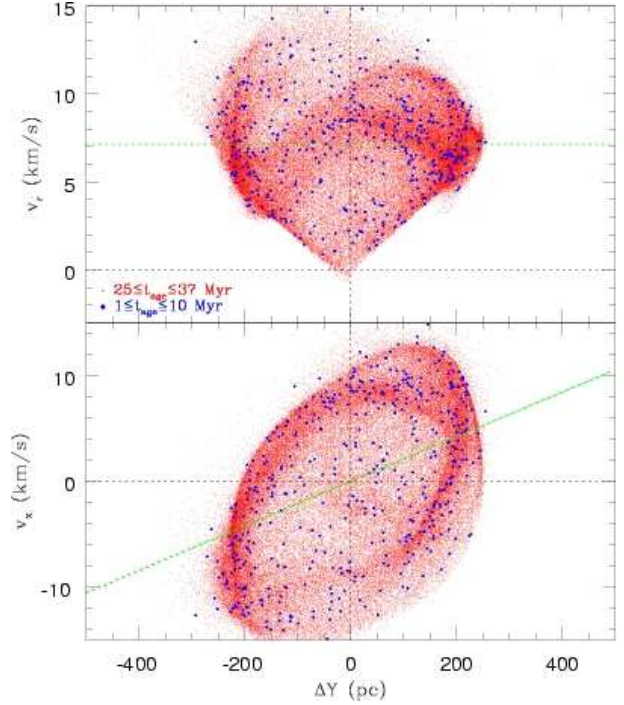
Fig. 1 shows that as the DMC passes through the cloud from its beneath ( $T = 7$  Myr), it first compresses the central region of the cloud so that new stars can form from the high-density region of the cloud ( $T = 7 - 15$  Myr). Star formation rate increases rapidly during the collision ( $T = 8$  Myr), reaches its maximum of  $0.16 M_\odot \text{ yr}^{-1}$  ( $T = 12$  Myr), and rapidly decrease to be  $0.005 M_\odot \text{ yr}^{-1}$  after the collision ( $T = 22$  Myr). The dark impact then induces an outwardly propagating density wave and consequently transforms the



**Figure 3.** Time evolution of the distance between the gas cloud and the DMC (left) and the projected distribution of new stars in the simulated stellar structure at  $T = 45$  Myr (right). The dotted thick green line indicates the initial cloud radius ( $=200$  pc) and the intersection between the line and the thick solid green line for the cloud-DMC distance can indicate the time when the cloud and the DMC start their strong dynamical interaction in the left panel. The dotted red lines indicate the start and the end of active star formation (i.e., starburst) during the dark impact in the left panel. The two dotted blue lines indicate a range of younger stellar populations with ages ( $t_{\text{age}}$ ) between 1 Myr and 10 Myr in the left panel. The starburst population with  $25 \text{ Myr} \leq t_{\text{age}} \leq 37 \text{ Myr}$  and younger one with  $1 \text{ Myr} \leq t_{\text{age}} \leq 10 \text{ Myr}$  are shown by smaller red dots and bigger blue ones, respectively in the right panel. Here  $\Delta X$  and  $\Delta Y$  denote  $X$ - and  $Y$ -positions of particles with respect to the mass center of the stellar structure. The direction of the Galactic center (G.C.) is shown by a green arrow. The center of the frame is set to be the mass center of the stellar structure so that the simulated distribution can be compared with the observed one (Poppel 1997; Perrot & Grenier 2003).

oblate gas cloud into the ring-like one ( $T = 22$  Myr). The tidal torque of the dark impact also causes the precession of the internal spin vector of the new stellar system so that the system can be seen as significantly inclined with respect to the Galactic plane ( $T = 22$  Myr). The gas and new stars in the cloud can continue to expand after the dark impact, while the inclination angle of the stellar system becomes apparently smaller in edge-on view owing to precession ( $T = 30$  Myr). The strong tidal field of the Galaxy transforms the expanding stellar system into an elongated ring-like structure that is still inclined to the Galactic plane ( $T=45$  Myr).

Fig. 2 shows that the simulated ring-like structure can be seen as a giant arc across the Galactic plane if it is projected onto the Galactic coordinate system. The arc-like appearance is due to the disk-like distribution of gas and stars inclined to the Galactic plane. The simulated arc-like belt can cover the observed OB stellar associations that are considered to be formed in the GB, which suggests that the present model can reproduce well the distribution of young stellar populations in the GB. The DMC is currently located at  $(X, Y, Z) = (-6.3, -1.0, 1.4)$  kpc and the distances of the DMC from the Galactic center and the Sun are 6.5 and 2.8 kpc, respectively. Fig. 3 shows that the projected distribution of older stars with stellar ages ( $t_{\text{age}}$ ) ranging from 25 Myr to 37 Myr (corresponding to stars formed between  $T=8$  Myr and 20 Myr, i.e., during a starburst) with respect to the mass center of all stars appears to be ringed and moderately



**Figure 4.** Kinematics of the simulated stellar structure. The radial velocities ( $v_r$ ) and  $X$ -components of velocities ( $v_x$ ) for new stars with  $25 \text{ Myr} \leq t_{\text{age}} \leq 37 \text{ Myr}$  (smaller red dots) and with  $1 \text{ Myr} \leq t_{\text{age}} \leq 10 \text{ Myr}$  (bigger blue dots) are plotted against  $\Delta Y$  in upper and lower frames, respectively. Here  $v_r$  and  $v_x$  are velocity components with respect to those of the mass center of the stellar structure. The dotted green lines in the upper and lower panels represent the mean value of  $v_r$  ( $= 7.1 \text{ km s}^{-1}$ ) for all stellar particles and rigid rotation with an angular velocity of  $21.1 \text{ km s}^{-1} \text{ kpc}^{-1}$ , respectively.

elongated. The distribution of the very young stars with  $1 \text{ Myr} \leq t_{\text{age}} \leq 10 \text{ Myr}$  also appears to be ringed, though a significant fraction of the stars exist inside the ring-like structure. The elongated morphology and size of the GB in the present simulation are similar to those in the previous dynamical models for the observed properties of the GB (Perrot & Grenier 2003).

Fig. 4 shows that almost all stars have positive radial velocities ( $v_r$ ) with a mean  $v_r$  of  $7.1 \text{ km s}^{-1}$ , which means that the simulated stellar structure is expanding with respect to its mass center. The expansion rate of the structure at  $\Delta Y = 400$  pc is  $17.9 \text{ km s}^{-1} \text{ kpc}^{-1}$ , which is quite similar to that ( $20 \text{ km s}^{-1} \text{ kpc}^{-1}$ ) derived from one of kinematical models of the GB (Lindblad 2000). Although there is a weak tendency that the outer stars are more likely to have larger  $v_r$ , the distributions of the stars in this  $\Delta Y$ - $v_r$  phase space is highly inhomogeneous owing to random motion of stars. Fig. 4 also shows that stars with positive  $\Delta Y$  are more likely to have positive  $v_x$ , which means that the simulated structure has internal rotation with the direction consistent with that of the Galactic disk. The velocity gradient of  $v_x$  for  $|\Delta Y| \leq 400$  pc is  $21.1 \text{ km s}^{-1} \text{ kpc}^{-1}$ , which is comparable to the angular velocity of  $7\text{--}24 \text{ km s}^{-1} \text{ kpc}^{-1}$  derived from a kinematical model based on observational data sets of stars in the GB (Lindblad 2000).

## 4 DISCUSSION AND CONCLUSIONS

By using the standard formula for the timescale of collision/merging, the time scale of a cloud-DMC collision event ( $t_m$ ) can be estimated as follows (Makino & Hut 1997);

$$t_m = \frac{1}{n_h \sigma v}, \quad (1)$$

where  $n_h$ ,  $\sigma$ , and  $v$  are the mean number density of the DMCs within the Galaxy halo, the geometrical cross section of gas clouds and a relative velocity between a DMC and a cloud. We here estimate  $n_h$  for the central 50 kpc of the Galaxy (corresponding to the pericenter of the LMC orbit) and assume that  $v$  is the same as one-dimensional velocity dispersion ( $= v_c/\sqrt{2}$ ), where  $v_c$  is the circular velocity thus  $220 \text{ km s}^{-1}$ ) of the Galaxy halo. If we use the results of the latest cosmological simulations, we can estimate the total number of DMCs ( $N_h$ ) with masses larger than  $\sim 10^7 M_\odot$  within 50 kpc (Diemand et al. 2008). The total number of subhalos in the latest high-resolution cosmological simulation (Springel et al. 2008a) is by a factor of  $\sim 8$  larger than that of Via Lactea II (Diemand et al. 2008). Considering this resolution effect, we adopt  $N_h = 100$  rather than  $N \approx 20$  (Diemand et al. 2008) in the estimation of  $t_m$ .

We here estimate  $t_m$  for a DMC to collide with one of many GMCs (not with a specific GMC). Therefore  $\sigma$  should be  $N_{cl} \times \pi \times R_{cl}^2$ , where  $N_{cl}$  and  $R_{cl}$  are the total number of the massive GMCs in the Galaxy and their sizes, respectively. Given that the Galaxy has  $\sim 4000$  massive GMCs (Solomon et al. 1987) with masses more than  $10^5 M_\odot$ , we can derive  $t_m$  for  $N_{cl} = 4000$  as follows;

$$t_m = 0.26 \left( \frac{N_h}{100} \right)^{-1} \left( \frac{R_{cl}}{100 \text{ pc}} \right)^{-2} \left( \frac{v}{156 \text{ km s}^{-1}} \right)^{-1} \text{ Gyr} \quad (2)$$

This suggests that the cloud-DMC collision is not rare and thus that the dark impact can inevitably influence evolution of the Galactic disk to some extent. The collisions between DMCs with lower masses ( $M_{dm} \sim 10^6 M_\odot$ ) and less massive GMCs (with masses less than  $10^5 M_\odot$ ) can be much more frequent than those described above, because a much larger number of these less massive DMCs are predicted to exist in the Galactic halo (Diemand et al. 2008). These collisions between less massive DMCs and GMCs can form significantly smaller (thus less clearly visible) stellar structures in comparison with the GB.

The present study has first demonstrated that the dark impact can dramatically change spatial distributions of forming stars and star formation histories within giant molecular clouds. This new mode of star formation is in a striking contrast to those resulting from small-scale turbulence within clouds (e.g., Larson 1981) and from global galaxy-scale dynamical instability (Elmegreen 1995). Future observational studies of stars in the GB by GAIA (Perryman et al. 2001) will determine the three-dimensional structural and kinematical properties of the GB stars and the individual stellar ages and thus enable us to compare the results with those of the present study. This comparison will determine whether and when the majority of stars in the GB were formed from a single collisional event of a DMC in a more quantitative way. The GB is not just a magnificent stripe of stars in the night sky but also a fossil record containing profound physical meanings of a dramatic event which would have happened in the solar neighborhood.

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